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NUCLEAR EXPLOSIONS—PEACEFUL APPLICATIONS (TID-4500)

# MECHANICAL EFFECT OF UNDERGROUND NUCLEAR EXPLOSIONS, MOSCOW, USSR, 1969

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## FOREWORD

This report is one of three recently released by the Soviet Union to the U. S. Mission and the International Atomic Energy Agency in Vienna, Austria. The reports discuss the use of nuclear explosions for industrial and construction projects in the Soviet Union, the results of two experimental detonations that were recently conducted in the USSR, and general theory developed as a result of such experiments.

The two other reports are: Review of Possible Peaceful Applications of Nuclear Explosions in the National Economy of the Soviet Union and Radioactive Contamination of the Environment by Underground Nuclear Explosions, and Methods of Forecasting It.

These reports were translated by Mr. Grimes of AZTEC, Inc. and were edited for technical accuracy and terminology by M. Nordyke of the Lawrence Radiation Laboratory, Livermore, California.

MECHANICAL EFFECT OF UNDERGROUND NUCLEAR EXPLOSIONS

Moscow USSR — 1969

Report of the Institute of Terrestrial Physics
of the USSR Academy of Sciences

## INTRODUCTION

1. Chemical explosives are widely used in various fields of industry and construction. Explosions aid in excavation while building hydraulic-engineering installations, in uncovering ore deposits, in crushing hard rock, in generating elastic waves during seismic investigations, etc.

A sufficiently large body of experience has been accumulated in the use of such explosions in relation to the areas listed to permit us to use the explosive energy with considerable efficiency. The problems of safety during explosions have been well established.

The theory of explosion in a solid medium has been studied to a much lesser degree and the part played by the theory was actually limited to the analysis of problems of similitude and the formulation of principles for the presentation of empirical formulae.

2. The mechanical effects of nuclear explosions do not differ qualitatively from those of chemical explosions; therefore, the possibility of using nuclear explosives in the same fields where chemical explosives are being used is beyond any doubts.

The experimental data, although still scarce, indicate that, for all practical purposes, nuclear cratering explosions do not differ from chemical explosions.

3. Nuclear charges present quite a few advantages, including small dimensions and practically unlimited power, thus opening up new possibilities for using the explosion and laying the groundwork for a totally new technological process in a number of industrial and construction fields. We should bear in mind in this connection the planned construction of hydraulic installations of large dimensions, the intensification of oil and gas recovery, and the building of underground storage facilities, all of which may be achieved only with the aid of nuclear explosions.

4. The particular properties of a nuclear explosion generate certain difficulties in determining the mechanical effect; these difficulties may be described in general as follows:

The change in the scale of the phenomenon when chemical explosive charges are replaced by nuclear charges is so considerable that the empirical rules previously established may prove to be incorrect. (For instance, the dependence of the crater dimensions upon the explosive energy.) The high initial energy concentration in the explosion of a nuclear charge means that the thermodynamic

properties of the gasiform working substance which transfers the explosion energy to the surrounding medium while expanding actually depends upon the properties of the rock. We can expect that the thermodynamic parameters of the gaseous products of a nuclear explosion will differ widely, depending upon the rock.

5. An underground nuclear explosion is a complex phenomenon, and its description by stages seems to be a waste of time since we shall encounter countless unsolved problems in the process, which will in no way clarify the possibilities of a practical use of the explosion.

If, however, we decide to analyze the concrete purpose of an explosion, the necessary detailed description of the phenomenon and an adequate evaluation of the desired effects may be obtained with ease even at the present level of knowledge.

Keeping in mind the pertinent applications possible at the present time, we attempted to isolate the basic parameters of the explosion effect and analyze prediction methods. We also investigated certain unsolved problems important for practical applications.

## BASIC PARAMETERS OF THE MECHANICAL EFFECT OF AN UNDERGROUND EXPLOSION

6. The mechanical effect of a camouflet explosion is characterized by:

volume of the cavity
dimensions of the fracture zone
degree of fracturing attained by the rock
intensity of the compression wave at various distances from the explosion epicenter
seismic effect.

The mechanical effect of a cratering explosion is characterized by:

dimensions of the visible crater
distribution of the ejected ground on the free surface
seismic effect.

In addition, the stability of the cavities and crater slopes is of great importance in large-scale explosions.

7. The basic parameters of the mechanical effect of the explosion listed above, needless to say, do not present a full picture of the multiple changes brought about in the medium surrounding the charge.

However, in our opinion, practically all effects observed and presently used may be presented as functions of the basic parameters listed above.

8. Although a rough connection between basic parameters can be found for explosions occurring in media with properties that are sufficiently simple and that have been thoroughly studied, they must, in the majority of cases, be considered independently.

The level of modern science calls for working out a necessary evaluation method (mostly empirical or semi-empirical) for each of the parameters indicated.

## INITIAL PARAMETERS OF A NUCLEAR EXPLOSION

9. The initial parameters of chemical explosions are determined by the properties of the explosives used: energy, density, detonation rate, adiabatic curve of detonation products expansion.

The limited variation of density and specific energy in conventional explosives has but a small effect upon the mechanical effect of an underground explosion. The same statement can be made about the adiabatic curve of detonation products.

Thus, the only characteristic property of the charge of a chemical explosion is its energy.

10. A nuclear charge differs from a chemical one in that it provides a considerable variation in the initial pressure (energy density) in the charge chamber. The role of this parameter in the area of low initial energy concentrations is quite considerable. It is sufficient to remember that it is possible to decrease the seismic effect of an underground explosion of a given energy by a factor of 2 by increasing the volume of the charge chamber.

However, in the case of a high initial energy concentration, when the pressure in the charge chamber exceeds $\rho c^2$ ($\rho$ = medium density, c = propagation rate of longitudinal waves) of the surrounding medium, the influence of the indicated parameter upon the mechanical effect of the explosion will be almost nil.

An analogous situation exists, for instance, in an explosion in the atmosphere.

11. The region within whose limits a shock wave (of such intensity that rock is transformed into gas) is propagated may be compared to a chemical explosion of a highly effective bursting charge. The linear dimensions of such an effective charge in a given rock will vary in proportion to the cube root of the explosion energy.

Thus, the only parameter characteristic of a nuclear charge in explosions with a high initial concentration of energy is the full explosion energy. This characteristic makes possible a wide use of various considerations of similarities while analyzing the material tested and while working out prediction methods concerning the mechanical effect.

12. The properties of the gaseous products of a nuclear explosion are determined by the compressive property of the rock and its chemical content. Therefore, the initial parameters of explosions of similar energy performed in different rocks are, generally speaking, not similar.

However, the effect of this dissimilitude in the initial stages of explosions upon the mechanical effect should not be exaggerated, since the dissipation of energy in the area nearby is relatively low. (Several percent of the full explosion energy is spent on evaporation and fusion.)

Other, far more delicate processes of energy exchange between the gaseous and the condensed phases in a layer of heated rock are much more essential. It is possible to presume that the presence of moisture in the rock (or of any other components strongly affected and easily vaporized) may promote the use of the energy spent initially on the heating of the medium by the shock wave. By this means, the energy of the gaseous phase will be replenished during later stages, at the time when the general energy potential decreases considerably and this change may become noticeable.

13. In view of the above, it should be clear that the computations on the movement of the medium during the initial stage of the explosion (at the time when the specific properties of solid substances have not yet been made apparent) do not present any particular interest for the prediction of the mechanical effect of an explosion. In a great many cases, the use of the simplest computation provides the correct order of magnitude of the basic kinematic parameters. These computations serve only for an evaluation of the energy dissipation in the initial stage.

## PREDICTION METHODS FOR THE MECHANICAL EFFECT OF A CAMOUFLET EXPLOSION

### (a) Dimensions of the camouflet cavity

14. Experimental data on the dimensions of camouflet cavities formed as a result of underground nuclear explosions can be presented in a comparatively small table. (Table 1)

Table 1

| Explosion | Medium | Explosion energy, E, kilotons | Depth of charge, W, in m | Average density of overlying rock, $\rho$, in $g/cm^2$ | Cavity radius $R_n$, in m |
|---|---|---|---|---|---|
| Rainier | tuff | 1.7 | 2.74 | 1.9 | 19.8 |
| Logan | tuff | 5.0 | 283 | 1.8 | 28.0 |
| Blanca | tuff | 19.2 | 301 | 1.8 | 44.2 |
| Antler | tuff | 2.5 | 402 | 1.9 | 19.8 |
| Platte | tuff | 1.7 | 191 | 2.2 | 21.6 |
| Mad | alluvium | 0.43 | 181 | 1.8 | 11.3 |
| Stillwater | alluvium | 2.7 | 181 | 1.8 | 24.7 |
| Brazos | alluvium | 7.8 | 256 | 1.8 | 27.7 |
| Cimarron | tuff-alluvium | 11.2 | 305 | 1.8 | 32.6 |
| Hoosic | tuff-alluvium | 3.1 | 187 | 1.8 | 25.9 |
| Hardhat | granite | 5 | 286 | 2.7 | 19.2 |
| Shoal | granite | 12.5 | 367 | 2.7 | 25.6 |
| Gnome | salt | 3.1 | 361 | 2.3 | 17.4 |
| Salmon | salt | 5.3 | 827 | 2.25 | 17 |
| Handcar | dolomite | 12 | 403 | - | 21.2 |

The conditions for the performance of each test are characterized by the explosion energy, the depth of the charge, and the mechanical properties of the rock.

The variation of the conditions is admittedly insufficient for the clarification of any rules by means of purely empirical methods. It is therefore necessary to consider additional ideas in order to interpret experimental data.

15. Considerations of similarities are the most reliable ones. Experience shows that the dimension of the cavity is proportional to the explosion energy in similar rocks and at similar depths. This simple rule serves as a basis for the computation of empirical formulae.

16. The dependence of the cavity dimensions upon the rock properties is very great. Results of chemical explosions indicate that the volume of cavities per unit energy in various rock may differ by more than an order.

Investigations conducted during the past few years in the Institute of Terrestrial Physics of the USSR Academy of Sciences permit us to connect the maximum dimensions of the camouflet cavity with the strength and elasticity of the rock.

This is the structure of the relation obtained:

$$\frac{V\rho c^2}{E} = f\left(\frac{\sigma^*}{\rho c^2}\right)$$

where V – maximum volume of cavity
E – full explosion energy
$\rho$ – rock density
c – velocity of longitudinal waves
$\sigma^*$ – radial stress on the boundary of the elastic zone.

17. The role played by the depth at which the charge has been placed is considered from two points of view. The first opinion, widely disseminated due to American studies, states that the expansion of the cavity is discontinued when the pressure of the gases in the cavity equals the lithostatic pressure. It is understood that the maximum cavity volume and the final volume, recorded a long time after the explosion, coincide.

A comparison with experimental data obtained during an explosion in salt confirms, in the opinion of the proponents of this opinion, the results of the computation.

The second opinion can be stated as follows: At depths where the lithostatic pressure is lower or equal to the crushing strength of the material, the change in the maximum dimensions of the cavity (depending upon the depth) is connected with the change in the properties of the rocks and the conditions of their destruction.

18. At present, individual facts have been accumulated which lead to the assumption that the cavity, upon reaching its maximum dimensions, undergoes a certain compression. Thus, for instance, according to evaluations made by the Institute of Terrestrial Physics of the USSR Academy of Sciences, the maximal cavity volume in the "Salmon" and "Gnome" explosions exceeded the final volume by 2 and 1.5 times, respectively.

The possibility of cavity compression has been established by means of special laboratory tests.

19. The conditions of stability of the underground cavity remains not quite clear, even now. It is known that, as a result of the collapse of the cavity, a column of crushed rock is formed, of a height equal to about five to six cavity radii.

However, we ignore the stability conditions as well as the conditions of collapse, which most probably do not coincide and allow for quasi-stable conditions.

(b) Dimensions of the zones of fractured rock

20. It is extremely difficult to observe directly the fractured or crushed zones after underground explosions. In addition, there is always a certain arbitrariness in determining the concept of "fracturing" of a rock medium, which, from the start, represents a non-homogeneous medium perforated by a network of cracks.

The following objective criteria of fracturing or crushing may be indicated: the irreversible deformation of rock blocks; the heating up of the medium; microcracks; the formation of a network of new cracks; change in the elastic properties of the rock; individual elongated cracks.

However, the wide use of the criteria indicated in describing the fracture zone has not yet been methodically secured.

In certain cases these general criteria are insufficient, since a considerably more concrete result is needed for working out technological application schemes and there is no possibility of obtaining such criteria except by means of an actual experiment.

21. An investigation of the parameters of the compressive wave during an underground explosion, which can be recorded with sufficient reliability, may provide the most reliable information on the dimensions of the irreversible deformation zone.

When evaluated by this method, the radius of the fracture zone exceeds the radius of the underground cavity by approximately one order. Such an evaluation presents the maximum dimension, since beyond the indicated limits of the boundary, the medium behaves almost like an elastic body.

22. The volume of rock fractured increases (in accordance with the law of similitude) in proportion to the explosion energy. (No effect of relaxation processes during the fracturing of rock by explosion has been uncovered by tests.) This circumstance allows us to obtain (by a sensible selection of the scale of the test explosion and consideration of the scale of the heterogeneity of the rock massif) the necessary information on the character of rock fracturing and on the dimensions of fractured zones by using experimental models.

(c) The character of fracturing of rock by the explosion

23. The character of the fracturing is determined, first of all, by the rock properties and the geological structure of the massif. The possibilities of controlling the process of the explosive fracturing are extremely limited as far as this situation is concerned. Some results may be obtained by an appropriate distribution of individual charges in a multi-charge explosion, since such methods are being applied in the mining industry.

(d) The compressive wave

24. Numerous measurements of the parameters of the compressive wave during underground nuclear explosions provide us with a series of important conclusions.

The maximum velocity of the medium displacement in the wave ($V_{max}$) is the most stable and relatively easily recorded parameter.

The amplitude of the displacement velocity in explosions with different energies but in similar rock at distances proportional to the explosion scale are equal.

The amplitude of the displacement velocity does not depend to any large degree upon the properties of the rock. Thus, for instance, in explosions made in granite, the dependence of the wave amplitude upon the distance and explosion energy is as follows:

$$V_{max} = 7\left(\frac{q^{1/3}}{R}\right)^{1.6}$$

while in explosions in rock salt it is:

$$V_{max} = 10\left(\frac{q^{1/3}}{R}\right)^{1.6}$$

where $[V] = m/sec$; $[q] = kg\ TNT$; $[R] = m$.

The time of the positive velocity phase is proportional to the radius of the destruction zone and, under equal conditions, increases with the explosion energy $\tau_+ = q^{1/3}$.

25. In spite of certain difficulties that arise in the analysis of empirical relations and that are due to the absence of a physical model for the energy dissipation of the mechanical effect in rock, the parameters of the compressive waves may be predicted, on the basis of accumulated experience, with a precision sufficient for practical applications.

(e) The seismic effect of an explosion

26. The seismic effect of an explosion is predicted by means of empirical relations.

The conditions of an explosion are characterized by the energy, the depth at which the charge is placed, and the properties of the rock in which the charge is placed.

The frequency-amplitude characteristics of the surface vibrations depend upon the geological structure along the propagation route of the seismic wave and upon the properties of the soil at the recording site.

The large number of parameters which determine the seismic effect do not allow us to obtain simultaneously both a high precision and a sufficient universality of empirical formulae.

27. In essence, the seismic process of an explosion includes three independent problems:

(1) the excitation of seismic waves due to the explosion;
(2) the propagation of seismic waves in heterogenous media;
(3) the effect of seismic vibrations upon the structures, including consideration of the properties of the foundation.

28. The first problem is actually reduced to a determination of the parameters for individual groups of waves in the immediate vicinity of the source (at distances on the order of the wave length), depending upon the conditions of the blast.

A distinction should be made between deep explosions in which the fracture zone is separated from the free surface by a layer of undisturbed soil, and explosions close to the surface.

In the case of deep explosions, the seismic wave is formed by a spherical compression wave and the equivalent source may be considered an expansion center.

In explosions performed close to the surface, the source has a complex nature and this is evident in the redistribution of energy between individual wave groups.

The experimental data available indicate that the force of gravity plays a considerable role in the process of formation of the seismic signal. The dependence of the seismic wave parameters upon the explosion energy does not, therefore, fit the frame of a simple geometric similitude.

29. The second problem consists in the finding of ways of accounting for the peculiarities of the geological structure along the propagation route of the seismic wave. The difficulties encountered are created by the fact that rocks under conditions of natural stratification present a rather heterogeneous medium, which differs considerably from an ideal elastic body.

The nature of energy absorption of elastic waves in rock has still not been clarified, although this factor plays an essential role in the process of transformation of the seismic signal.

30. The third problem is connected with the establishing of the boundaries of the safety zone from the standpoint of ground shock. It has been determined in an experimental manner (applicable to rather small explosions) that the maximum amplitude of displacement of the surface is the critical parameter which determines the danger zone for seismic effects.

This statement, in principle, was first formulated in the Soviet Union at the end of the 1930's and apparently has been generally accepted.

It has been established that damage to low-rise buildings and other similar structures becomes apparent when the amplitude of the velocity reaches approximately 10 cm/sec.

However, large nuclear explosions have demonstrated that this criterion is insufficient when the duration of the motion increases.

31. The seismic effect is an extremely important factor and determines in many cases both the possibility of conducting and the effectiveness of using underground nuclear explosions in previously developed industrial regions.

Keeping in mind the modern level of scientific achievements, it is absolutely necessary to conduct special experimental explosions, striving to identify possible seismic situations in the areas of planned work using nuclear charges. In this manner, a substantially greater reliability of prediction of the seismic effect may be achieved.

## METHODS OF PREDICTION OF THE MECHANICAL EFFECT OF CRATERING EXPLOSIONS

32. The parameters of a cratering explosion, such as the dimensions of the apparent crater, the volume of the ground ejected, and its distribution over the surface, are determined by means of empirical formulae.

The experience gained in using chemical cratering explosions has shown that the volume of the craters is proportional to the explosion energy. In accordance with the geometrical similitude law, the formula for calculating the charge has the following structure:

$$q = kW^3 f\left(\frac{R}{W}\right)$$

where W – the line of least resistance

R – the radius of the apparent crater

q – the weight of the charge

k – the coefficient which considers the properties of the rock and the efficiency of the explosives.

33. Experimental investigations of chemical cratering explosions have established a series of rules:

(a) The dimensions of the crater are determined by the magnitude of the kinetic energy of the ejected matter, which attains approximately 10 percent of the total energy of the explosion.

(b) The development of the ejection in time has three stages:

During the first stage, the motion of the medium is symmetrical, as it is in an underground explosion. The kinetic energy is transmitted by means of the compression wave, which simultaneously fractures the rock in the future crater.

The symmetrical growth of the cavity practically ends at the conclusion of the first stage.

During the second stage, the ejected rock noticeably increases its kinetic energy due to the plunger effect of gases in the cavity; this energy attains its maximum value when the top of the dome on the surface rises to a height equal to W. The dome of ground breaks up into individual pieces and the boundaries of the future crater begin to appear.

The third stage is the trajectory of pieces in the gravity field.

(c) The effect of the force of gravity upon the dimensions of the crater becomes noticeable as soon as the kinetic energy of the ejected rock and the work

of lifting of the soil dome completed at the time of its destruction become commensurate. Due to this fact, the limit of applicability of geometrical similitude in computing the charges accompanied by ejections may be determined.

It appears that in explosions of charges weighing 1,000 tons and more of TNT, the force of gravity plays a substantial role in the process of the formation of the crater and should be considered as one of the determining parameters. Quite naturally, this critical value of the charge depends upon the properties of the rock and may be much smaller in explosions made in loose soil.

34. In the light of statements made above on the development of a cratering explosion, two peculiarities of a nuclear explosion, already mentioned, acquire the greatest importance:

(1) The high initial energy concentration, thus stipulating the dependence of thermodynamic parameters of the explosion products upon rock properties;

(2) The large scale of the explosions, thus excluding the application of the geometrical similitude law when predicting the mechanical effect.

We may expect that the plunger effect of the gases in the second stage of crater development will (in the case of a nuclear explosion) depend to a considerable degree upon the moisture in the rock and upon the presence of minerals which discharge gaseous products during thermal decomposition.

A large-scale explosion involves the manifestation of the role of the force of gravity as well as the necessity to consider the changes in the mechanical properties of rock with depth.

Thus, for instance, the strength of the rock, the scale of heterogeneities, and the distribution of cracks may all change considerably, depending upon the depth; the methodology of their determination, even under conditions of natural stratification, has not yet been completely worked out.

The peculiarities of a nuclear explosion given above, combined with all ensuing consequences, make us doubt that the method presently used in the analysis of experimental data is sensible; this method aims at obtaining a single computation formula for the determination of the dimensions of the ejection crater.

35. The theoretical computations of a cratering explosion present a picture of the lifting of the dome of ground which conforms with practice. However, the importance of these results should not be exaggerated, since the condition of the medium and its behavior during large-scale deformations are not quite known yet. This circumstance hampers the formulation of the conditions which define the radius within whose limits the soil is ejected and precludes the computation of the dimensions of the apparent crater which is formed as a result of the failure of the slopes.

Research is strongly recommended on modeling explosions which would clarify the structure of the connections between the basic parameters of the process.

A special installation simulating cratering explosions in loose soils has been designed at the Institute of Terrestrial Physics of the USSR Academy of Sciences; this facility has provided us with very encouraging results, particularly, on the dependence of the crater radius upon the explosion energy.

36. The problems associated with seismic safety during cratering explosions are the same problems encountered during underground explosions, as we have already stated. It should be added that (for the most part) cratering explosions will be of the group type, which makes it necessary to study in great detail the problems of interference of waves excited by several or many sources.

37. In conclusion, we should emphasize once again that the unsolved problems listed above cannot raise any doubts as to the possibilities of an efficient use of nuclear explosions in industry and construction.

The experience necessary for a more accurate definition of predictions of the mechanical effects may be accumulated during the conduct of both types of explosions, industrial as well as investigative.